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Kinematic analysis of mélange fabrics: examples and applications from the McHugh Complex, Kenai Peninsula, Alaska

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Abstract

Permian to Cretaceous mélange of the McHugh Complex on the Kenai Peninsula, south-central Alaska includes blocks and belts of graywacke, argillite, limestone, chert, basalt, gabbro, and ultramafic rocks, intruded by a variety of igneous rocks. An oceanic plate stratigraphy is repeated hundreds of times across the map area, but most structures at the outcrop scale extend lithological layering. Strong rheological units occur as blocks within a matrix that flowed around the competent blocks during deformation, forming broken formation and mélange. Deformation was noncoaxial, and disruption of primary layering was a consequence of general strain driven by plate convergence in a relatively narrow zone between the overriding accretionary wedge and the downgoing, generally thinly sedimented oceanic plate. Soft-sediment deformation processes do not appear to have played a major role in the formation of the mélange. A model for deformation at the toe of the wedge is proposed in which layers oriented at low angles to σ_1 are contracted in both the brittle and ductile regimes, layers at 30–45° to σ_1 are extended in the brittle regime and contracted in the ductile regime, and layers at angles greater than 45° to σ_1 are extended in both the brittle and ductile regimes. Imbrication in thrust duplexes occurs at deeper levels within the wedge. Many structures within mélange of the McHugh Complex are asymmetric and record kinematic information consistent with the inferred structural setting in an accretionary wedge. A displacement field for the McHugh Complex on the lower Kenai Peninsula includes three belts: an inboard belt of Late Triassic rocks records west-to-east-directed slip of hanging walls, a central belt of predominantly Early Jurassic rocks records north–south directed displacements, and Early Cretaceous rocks in an outboard belt preserve southwest–northeast directed slip vectors. Although precise ages of accretion are unknown, slip directions are compatible with inferred plate motions during the general time frame of accretion of the McHugh Complex. The slip vectors are interpreted to preserve the convergence directions between the overriding and underriding plates, which became more oblique with time. They are not considered indicative of strain partitioning into belts of orogen-parallel and orogen-perpendicular displacements, because the kinematic data are derived from the earliest preserved structures, whereas fabrics related to strain partitioning would be expected to be superimposed on earlier accretion-related fabrics.

1. Introduction

Tectonic mélanges are one of the hallmarks of convergent margins, yet understanding their genesis and relationships of specific structures to plate kinematic parameters has proven elusive because of the complex and seemingly chaotic nature of these units. Many field workers regard mélanges as too deformed to yield useful information, and simply map the distribution of mélange type rocks without further investigation. Other workers map clasts and matrix types, search for fossils or metamorphic index minerals in the mélange, and assess the origin and original nature of the highly disturbed rocks. This paper presents evidence that mélanges may preserve much more about their origin and history than generally appreciated.

One of the most persistent questions raised in mélange studies relates to the relative roles of soft-sediment vs tectonic processes of disruption and mixing. Many mélanges have been interpreted as deformed

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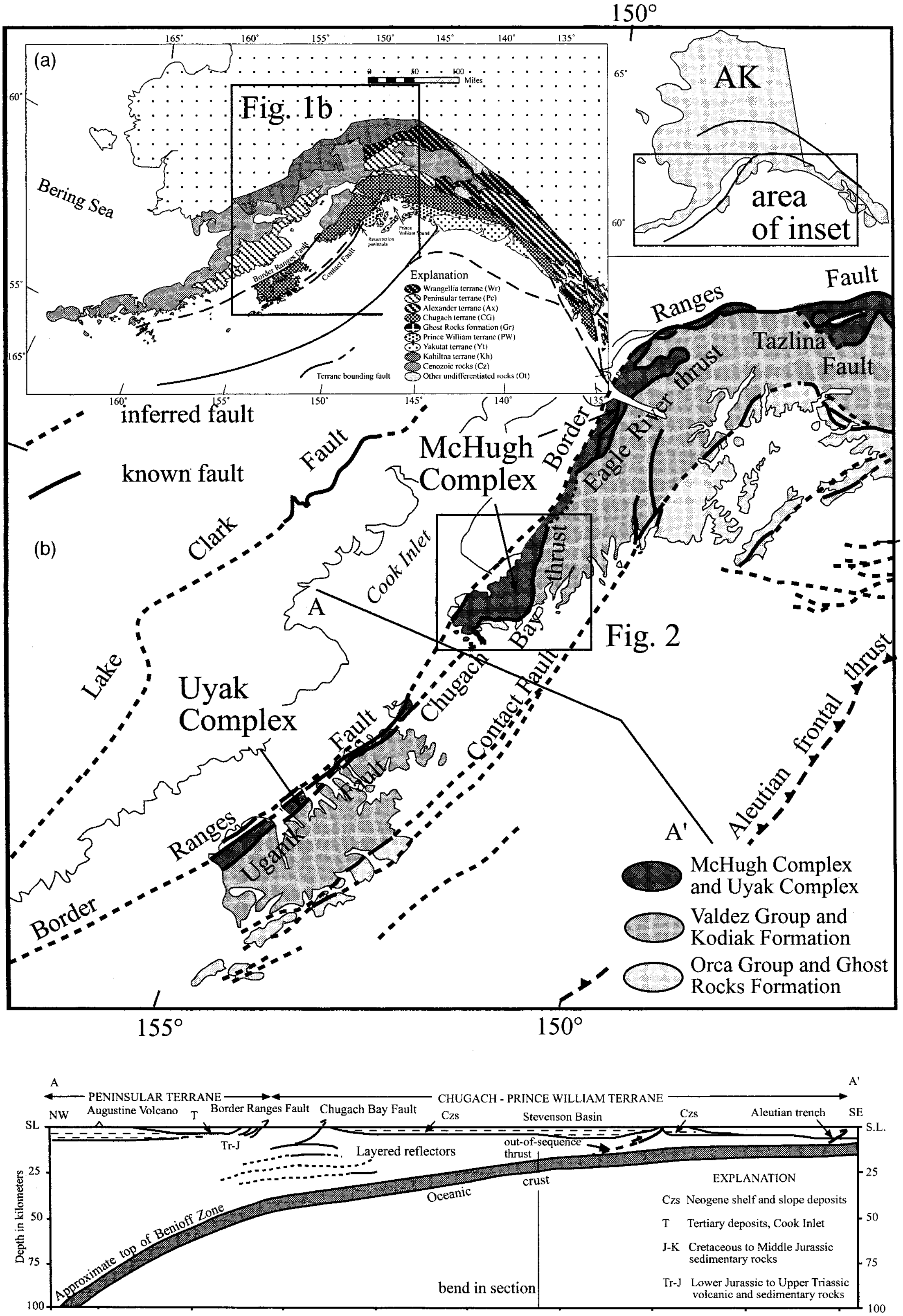

Fig. 1. Map of southern Alaska showing major tectonic elements including the McHugh Complex (and the equivalent Uyak Complex on Kodiak Island). Inset (a) shows tectonic setting of Chugach terrane to the south of the Wrangellia–Alexander–Peninsular superterrane. Detailed map (b) shows the McHugh Complex on the Kenai Peninsula, bounded on the west by the Border Ranges fault, and on the east by the Chugach Bay fault. Box shows location of Fig. 2.

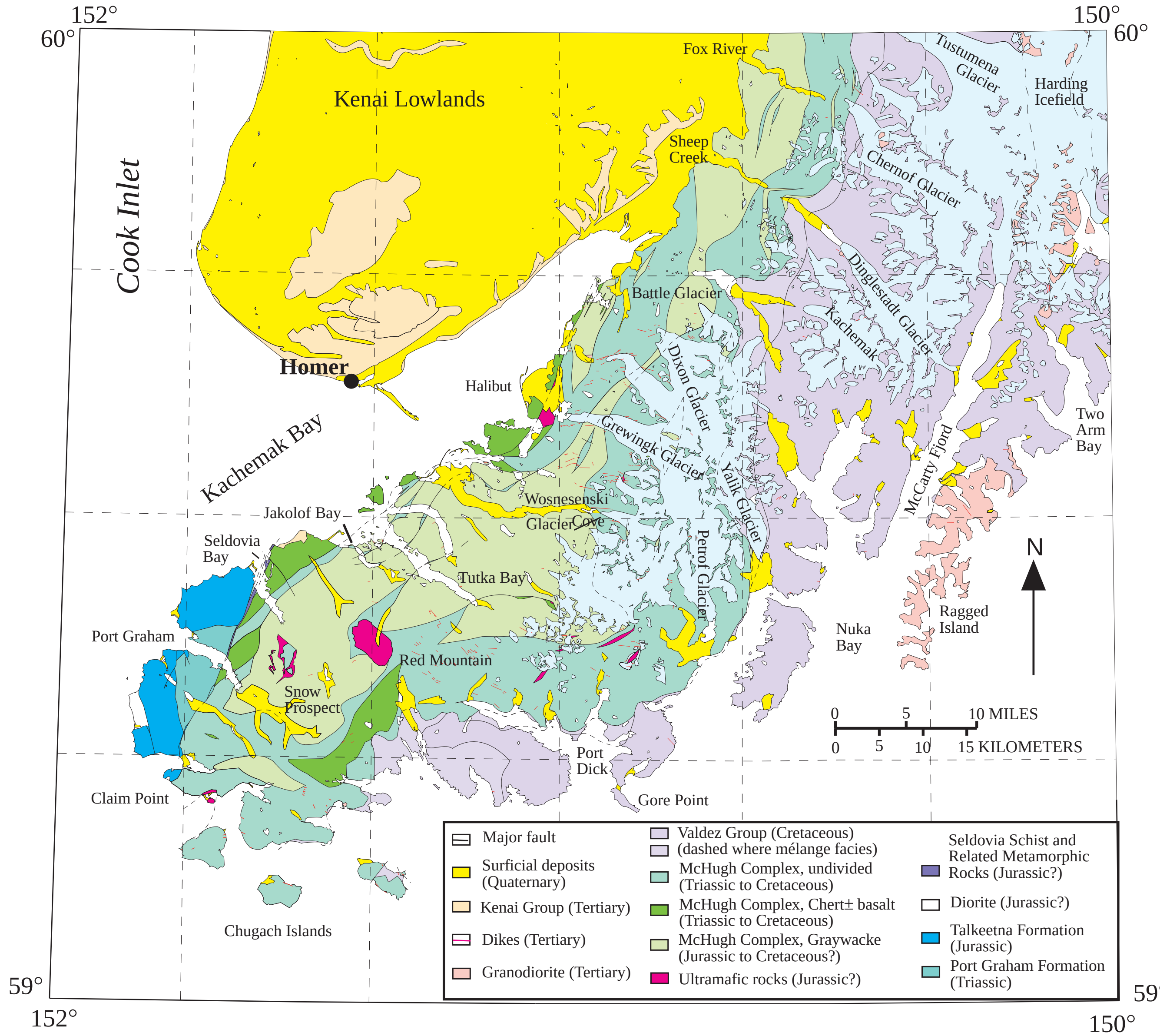

Fig. 2. Simplified geologic map of part of the Seldovia Quadrangle showing major tectonic elements and location of areas discussed in text (simplified after Bradley et al., 1999a).

olistostromes (sensu Flores, 1955), whereas other models attribute disruption entirely to tectonic or diapiric processes. Detailed structural studies have the potential to differentiate between these three end-member models, in that soft-sedimentary and some diapiric processes will produce clasts, which may then be subjected to later strains, whereas purely tectonic disruption will have a strain history beginning with continuous or semi-continuous layers, which become extended parallel to initial layering. Detailed field, kinematic, and metamorphic studies may be able to further differentiate between mélanges of accretionary tectonic vs diapiric origin (e.g. Byrne and Fisher, 1990; Orange, 1990). This paper presents structural observations at regional, outcrop, and hand-sample scales, that bear on the relative roles of soft-sediment, diapiric, and tectonic processes in the formation of a very extensive mélange, the McHugh Complex of southern Alaska (Fig. 1). Most of the structures and disruption of layering in the McHugh Complex is attributed to tectonic deformation, with very minor roles assigned to diapirism and soft sedimentary processes.

Analysis of deformational fabrics in tectonic mélange such as the McHugh Complex may also yield information about the kinematics of past plate interactions (e.g. Le Pichon et al., 1988; Platt et al., 1988; Kano et al., 1991; Byrne and DiTullio, 1992; Cowan and Brandon, 1994; Onishi and Kimura, 1995; Kusky et al., 1997a; Hashimoto and Kimura, 1999). Of these studies, only Kano et al. (1991), Cowan and Brandon (1994), and Onishi and Kimura (1995) used asymmetric fabrics generated during early stages of the mélange-forming process to infer plate kinematic parameters. In this paper a methodology for using kinematic data derived from tectonic mélanges in accretionary prisms is developed to derive information about the slip vector directions within an accretionary wedge setting. This information may ultimately prove useful for reconstructing the kinematic history of plate interactions along ancient plate boundaries, or how this convergence was partitioned into belts of head-on and margin-parallel slip during oblique subduction (e.g. McCaffrey, 1991, 1992, 1996; Avé Lallemant, 1996).

2. Regional geologic framework

The McHugh Complex of south-central Alaska (Clark, 1973) and its lateral equivalent, the Uyak Complex of Kodiak (Connelly, 1978), is a mélange constituting part of the Chugach terrane of southern Alaska (Fig. 1). It is interpreted as a Mesozoic–Cenozoic accretionary prism formed by offscraping (and/or underplating) outboard of the present seaward margin of the composite Peninsular–Wrangellia–Alexander superterrane (Plafker et al., 1989; Bradley and Kusky, 1992; Kusky et al., 1997b). The McHugh Complex is subdivided (Fig. 2) into subparallel internally complex belts of chert, basalt, gabbro, graywacke, argillite, massive graywacke, ultramafic massifs, and other belts mappable macroscopically only as mélange (Martin et al., 1915; Magoon et al., 1976; Cowan and Boss, 1978; Bradley and Kusky, 1992; Bradley et al., 1999a). Mapping of the McHugh Complex at scales ranging from 1:250 000 through 1:1140, to 1:1, and examination of thin sections at magnifications of up to 250:1 revealed a scale invariance, with the thickness of slivers of individual rock types varying from a fraction of a millimeter in belts of mesoscale mélange, to a few kilometers in the more coherent belts.

The observations reported here were made in the Seldovia Quadrangle on the southern part of the Kenai Peninsula (Figs. 1 and 2), with emphasis placed on relations from specific areas in which glacial retreat has created excellent three-dimensional exposure, permitting detailed mapping (Bradley and Kusky, 1992; Bradley et al., 1999a). These areas include the recently deglaciated toes of Grewingk Glacier, Wosnesenski Glacier, Dixon Glacier, Battle Glacier, and Petrof Glacier (Fig. 2).

The evolution of the McHugh Complex and its equivalents can be broken down into three broad, somewhat overlapping phases: (1) formation of the igneous and sedimentary protoliths; (2) incorporation into a subduction complex ('accretion'), and attendant deformation and metamorphism; and (3) younger deformations. This paper focuses on the mechanisms and consequences of accretion of the various protoliths and develops a model for the generation of different structural elements found in the mélange. The formation and tectonic setting of the igneous and sedimentary protoliths are treated elsewhere (Kusky et al., 1997b; Bradley et al., 1999a), as are details of the later deformations (Bradley et al., 1993; Kusky et al., 1997a; Haeussler et al., 1999).

3. McHugh Complex on the Kenai Peninsula

The McHugh Complex on the Kenai Peninsula lies about 35 km above the modern Benioff Zone (Jacob, 1986; Ratchkovsky et al., 1997). The principal rock units in the area of Fig. 2 are from NW to SE: (1) Mesozoic volcanogenic strata of the Peninsular terrane, a magmatic arc that collided with interior Alaska during Jurassic or Cretaceous time; (2) overlying Tertiary strata of Cook Inlet forearc basin; (3) a Jurassic belt of blueschist facies metabasalt, metarhyolite, metachert, metagraywacke and marble located near the town of Seldovia; and (4 and 5) the McHugh Complex and Valdez Group—landward and seaward components, respectively, of a Mesozoic accretionary wedge. The McHugh Complex includes variably disrupted greenstone, Triassic to Cretaceous chert, argillite, Jurassic and probably Cretaceous graywacke and conglomerate, outcrop-scale mélange, and relatively rare blueschist, Permian limestone, gabbro, and ultramafic rocks. The interval during which the McHugh Complex was accreted along the outboard margin of the Peninsular terrane is not well known, but probably spanned most of the Jurassic (blueschist facies metamorphism in the Seldovia schist is Toarcian) through mid-Cretaceous (the age of the youngest chert unit in the McHugh Complex is Albian). A minimum age of accretion of the McHugh Complex is given by the age of the Valdez Group, which in the Seldovia quadrangle consists of Campanian (?) to Maastrichtian turbiditic graywacke, slate, and conglomerate. In some belts, these protoliths have been thoroughly disrupted to form Type I mélange (sensu Cowan, 1985). Both the McHugh Complex and Valdez Group were intruded after their main deformation by Paleocene–Eocene plutons and dikes of the Sanak–Baranof near-trench magmatic belt (Hudson, 1979; Bradley et al., 1993; Kusky et al., 1997a, b).

3.1. Protoliths of the McHugh Complex

Mafic volcanic rocks are a common constituent of the McHugh Complex, and include variably altered pillow basalt, hyaloclastic basalt, and massive basalt. The basalts are intimately associated with gabbroic complexes that locally make up most of the outcrop and form outcrop belts up to several km long (Fig. 2). Another widespread rock type, a very fine-grained, light-green rock that occurs in thin layers associated in places with basalt and elsewhere with chert and argillite, is commonly referred to as 'tuff' in the field; in thin sections, however, it is a cataclastically microbrecciated basalt.

Radiolarian-bearing ribbon chert is an abundant component of the McHugh Complex. The chert is typically gray or green, less commonly red or black, and is interbedded on the scale of a few centimeters with argillite. Chert sections are intensely faulted and disharmonically folded. At several places, mostly in Kachemak Bay (Fig. 2), radiolarian chert depositionally overlies pillow basalt. Precise radiolarian age determinations show that the base of the chert varies in age from Ladinan (Middle Triassic) to Aptian–Albian (C. Blome, written communication, 1994; Bradley et al., 1999a). The simplest, and preferred interpretation of the age distribution is that there is a single diachronous basalt unit overlain by a single diachronous chert unit (Bradley and Kusky, 1992). An alternative possibility, however, is that multiple units of basalt and chert are interstratified.

Graywacke is another abundant component of the McHugh Complex. Like the chert and basalt, graywacke occurs in fault-bounded slices up to several kilometers wide. The great width of the graywacke belts implies this unit was initially rather thick. In addition to the graywacke tracts shown in Fig. 2, there are innumerable slices too small to be shown on maps of this scale—the smallest graywacke slices form sub-mm scale lenses within argillite and are only visible in thin section. The graywacke and conglomeratic graywacke typically form massive, structureless bodies, which belong to submarine fan facies A and B of Mutti and Ricci Lucchi (1978). Bedding is seldom observed and even where visible, it generally cannot be traced far. Some graywacke occurs with up to 50% interbedded argillite. Sand/shale ratios and the few preserved sedimentary structures together suggest that these rocks probably originated as turbidites of facies C, D, and E of Mutti and Ricci Lucchi (1978). In one locality in Kachemak Bay, graywacke conformably overlies Pleinsbachian (Early Jurassic) radiolarian chert (C. Blome, written communication, 1994; Bradley et al., 1999a).

Variably deformed argillite is a major component of the McHugh Complex. Only in one area, Jakolof Bay (Fig. 2), is relatively undeformed, bedded argillite sufficiently predominant and widespread to be mapped at 1:63,360 scale. This rock is a matrix-rich siltstone characterized by well-defined bedding and a bedding-parallel cleavage, both of which dip very gently. In addition, argillite is also interbedded with chert and with turbiditic graywacke. With increasing deformation, originally well-bedded couplets of chert and argillite, and of graywacke and argillite, are pulled apart to varying degrees.

'Mesoscale mélange' is a field term used to describe a rock that consists at outcrop scale of one or more types of blocks set in a deformed argillite matrix. Some mesoscale mélange is monomict, containing blocks of chert or graywacke only; these mélanges can be readily interpreted as the end product of bedding disruption described above. The more interesting and problematic mélanges, however, typically contain a mix of clast types including basalt, chert, graywacke, and even limestone.

Blocks of limestone are scattered throughout the McHugh Complex; the largest are 50–100 m thick and 100–200 m long. The limestone is typically buff to light gray and fully recrystallized. In a few places, however, primary textures and fossils are preserved. Tethyan Permian fusilinids and conodonts are found in some of the blocks (Stevens et al., 1997; Bradley et al., 1999a). The limestones occur everywhere as ellipsoidal- or rhomboidal-shaped blocks surrounded by deformed argillite. In some places, limestone blocks clearly line up as strings of boudins and as partly dismembered beds, suggesting they were originally through-going beds that were disrupted by mélange-forming processes.

At least seven separate ultramafic bodies occur as fault-bounded slices within the McHugh Complex in the Seldovia quadrangle (Fig. 2). The largest (16 km^2) and best known is the Red Mountain ultramafic body, which Burns (1985) assigned to her Border Ranges ultramafic and mafic complex. It consists largely of cumulate-textured dunite, interlayered with less abundant pyroxenite, chromitite, and garnet pyroxenite (Guild, 1942; Toth, 1981). Several workers (e.g. Plafker et al., 1989) have suggested that rocks of the Border Ranges ultramafic and mafic complex (including Red Mountain) are klippen of the basal part of the Peninsular terrane. Kusky (1997) alternatively suggested that the ultramafic complexes in the McHugh Complex on the Kenai Peninsula may have a different origin from ultramafic rocks of the Border Ranges ultramafic and mafic complex, and be an integral part of the McHugh Complex.

Other known ultramafic bodies share enough key characteristics with Red Mountain that a comparable origin is likely. The body at Claim Point, which is largely under water (Fig. 2) consists of dunite and chro-

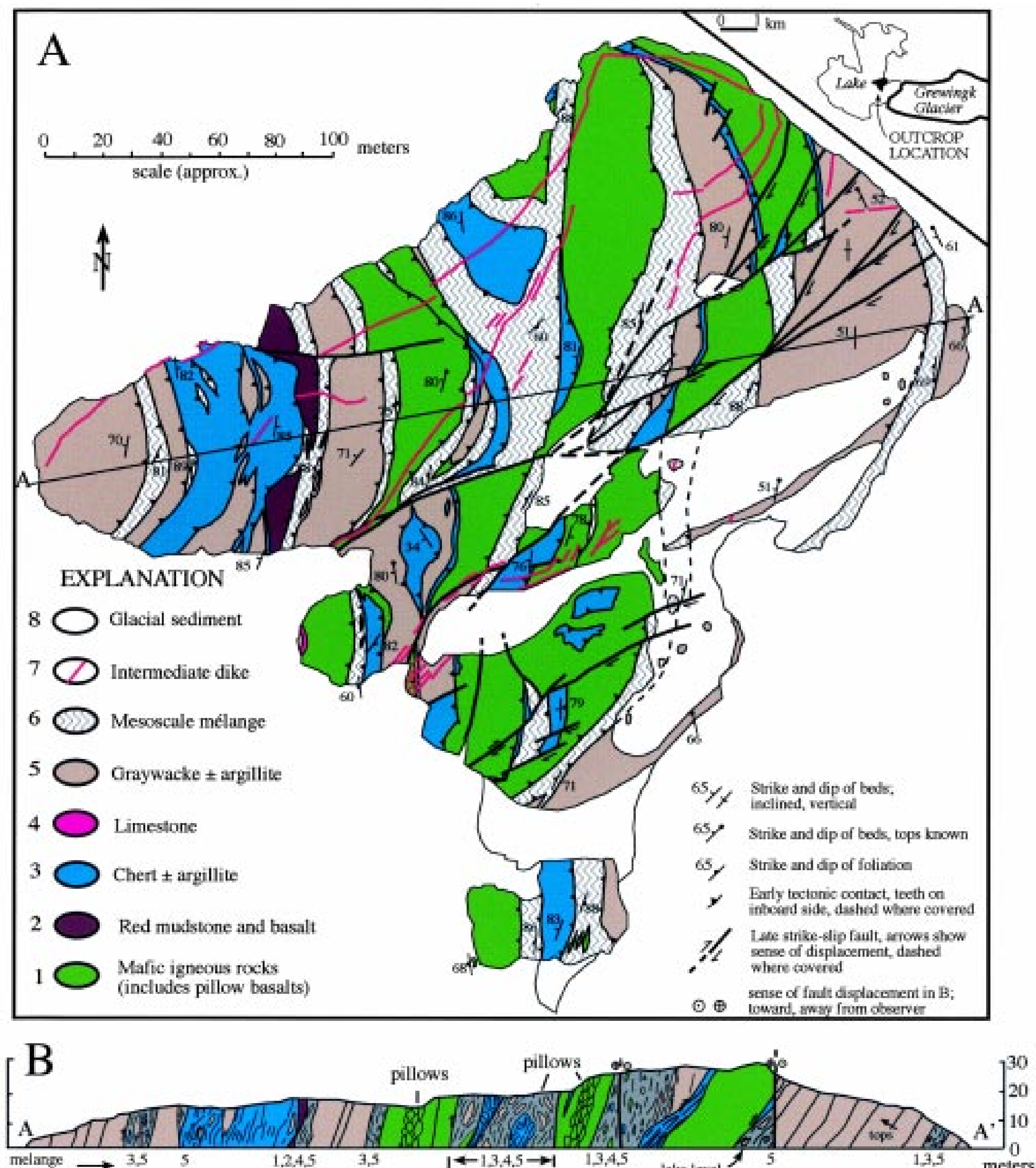

Fig. 3. (a) Structural map of mélange at the toe of Grewingk glacier (modified after Bradley and Kusky, 1992). (b) Detailed cross-section drawn along profile A–A′. Note the repetition of the basalt–chert unit three times across the map area, and the repetition of the argillite–graywacke units four times across the area. Scale is approximate because mapping was done using an enlarged aerial photograph as a base map.

mitite. The Snow Prospect (Fig. 2) consists of dunite, chromitite, serpentinite, and garnet clinopyroxenite, in two main fault slices. A small fault-bounded block south of Wosnesenski Glacier consists of dunite, chromitite, pyroxenite, serpentinite, and garnet clinopyroxenite. At Halibut Cove (Fig. 2), minor dunite, chromitite, garnet clinopyroxenite, and serpentinite are associated with gabbro and trondhjemite. The Halibut Cove body is also one of the largest of many fault slices of gabbro and trondhjemite on the Kenai Peninsula (Fig. 2). The gabbro consists of plagioclase, clinopyroxene, orthopyroxene, actinolite, apatite, and opaques. The trondhjemite consists predominantly of plagioclase and quartz. Other gabbro + trondhjemite slices west of Petrof Glacier are similar. In many places, gabbro is also intimately associated with basalt. Thus it appears likely that the ultramafic rocks, gabbro, and basalt may have a common origin (Kusky, 1997).

4. Description of mélange fabrics and kinematics

Mélanges are bodies of fragmented and complexly mixed rocks, but the nature of the fragmentation and mixing processes has remained elusive since the term was first proposed by Greenly (1919) for the Gwna mélanges of Anglesey. Few workers have attempted systematic analysis of mélange fabrics, nor used mélange fabrics to infer local structural or regional tectonic kinematics. Silver and Beutner (1980) summarized the results of a Penrose Conference on mélanges and proposed a now popular definition of mélanges as "mappable (1:25 000 or smaller scale), internally fragmented and mixed rock bodies containing a variety of blocks, commonly in a pervasively deformed matrix".

Mélange of the McHugh Complex exhibits two main phases of deformation. The first phase is characterized by a suite of generally ductile structures that formed the typical 'block in matrix' and disrupted aspect of the mélange (e.g. Bradley and Kusky, 1992). The second phase is characterized by generally brittle faults, dikes, and related structures (e.g. Kusky et al., 1997b). Each of these deformation phases could be subdivided into numerous events. This study focuses on the first, generally mesoscopically ductile phase of deformation, and describes the structures in two groups: those that contract lithological layering, and those that extend it. This convention avoids ambiguity in terms of relating 'contraction' and 'extension' to paleohorizontal, which may be difficult to determine considering the probable rotation of layering with respect to the stress field throughout a non-coaxial deformation history.

Analysis of asymmetric fabrics in mélange to determine local and regional kinematics has proven successful in a number of cases (e.g. Fisher and Byrne, 1987; Needham, 1987; Needham and Mackenzie, 1988; Taira et al., 1988; Waldron et al., 1988; Kimura and Mukai, 1989; Kano et al., 1991; Cowan and Brandon, 1994; Onishi and Kimura, 1995; Hashimoto and Kimura, 1999). As in the analysis of ductile and brittle shear zones, fabrics with monoclinic symmetry are regarded as yielding the most reliable indication of sense of shear (Kano et al., 1991). Asymmetric features are fairly abundant in mélange of the McHugh Complex, with interpretable asymmetric structures found in perhaps 30% of most outcrop belts. Outside of the disharmonically folded banded chert/argillite mélange units, these fabrics provide a kinematic framework for the deformation history of the mélange. In many respects, the mélange resembles a greatly enlarged view of a typical low-grade mylonite, and many of the principles of kinematic analysis in mylonite zones (e.g. Passchier and Trouw, 1996) can be applied to the McHugh Complex.

The sense of transport, shear, or rotation is indicated in many instances by offsets of distinctive horizons along minor faults. Asymmetric folds are common in banded chert layers, as well as in several types of mélange. In some instances, asymmetric tails around blocks, or the shapes of blocks or boudins, suggest a sense of shear. In a few zones of particularly intense shear, a *C–S* type (Bérthe et al., 1979) of composite planar fabric is present, which may be interpreted in a manner similar to structures in mylonite zones. The following sections describe the different common fabric elements found in the McHugh Complex and assess which structures yield kinematic information.

4.1. Contractional structures

4.1.1. Imbricated oceanic plate stratigraphy

Most of the structures contributing to the character of the mélange fabric extend layering at the scale of individual layers, yet paradoxically, the overall outcrop pattern (1:500 through regional scales) appears to repeat partial or complete packages of rock that have been internally extended. Rare preservation of original depositional contacts have been used to reconstruct an oceanic plate stratigraphy (Bradley and Kusky, 1992), and the present distribution of outcrop belts is in part a function of the style of imbrication acquired during offscraping, underplating, and continued deformation in the accretionary prism. Similar repetitions of an oceanic plate stratigraphy have been recognized in the correlative Uyak Complex of Kodiak Island, where Byrne and Fisher (1990) document that imbrication occurred after stratal disruption. The best-documented example of an imbricated oceanic plate stratigraphy is

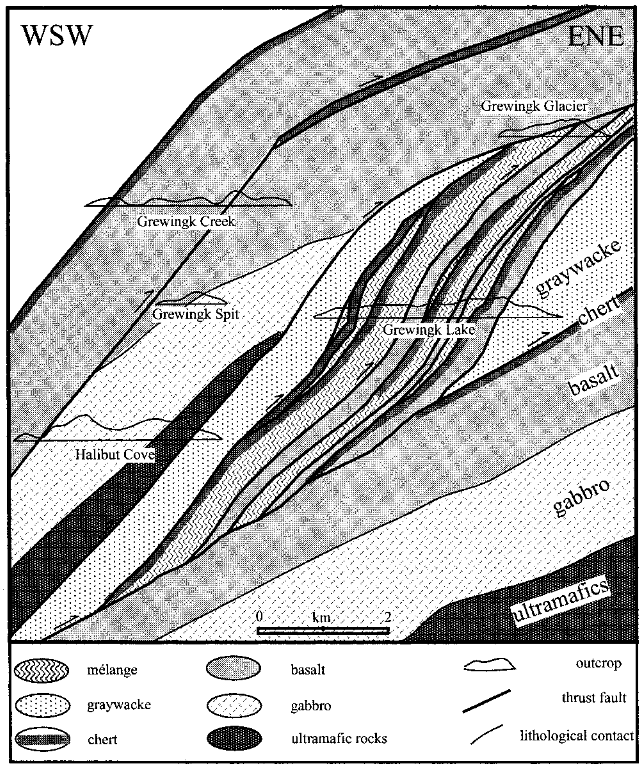

Fig. 4. Interpretative structural cross-section showing the repetition of the upper part of oceanic plate stratigraphy in a duplex structure. Structural control is provided by regional mapping and outcrops studied in detail, including Grewingk glacier, Grewingk creek, Grewingk spit, Halibut Cove, and Grewingk Lake (see Bradley et al., 1999a for locations). Note the Grewingk Lake outcrop section on this figure is a simplified version of that shown in Fig. 3(b). This section incorporates data from Bradley et al. (1999a), that shows a thicker scale of imbricate slices immediately to the south of Fig. 3(a), some of which include gabbro and ultramafic units at the base of the thrust imbricates. We interpret this to mean that the floor thrust steps down immediately south of Grewingk glacier, and the thrust imbricates bring up correspondingly deeper structural slices. The flattening of the structures into a roof thrust above the map area is conjectural.

provided by the map pattern at Grewingk Glacier (Fig. 3). Here, the gabbro–basalt–chert succession of oceanic plate stratigraphy is repeated three times, and the graywacke–hemipelagic argillite section is repeated four times, over a cross-strike distance of only 330 m. Fig. 4 is an idealized down-plunge projection showing the style of imbrication mapped in the Grewingk glacier/Halibut Cove area. Though simplified, this section shows some large thrust sheets containing relatively coherent sequences of graywacke–chert–basalt–gabbro $\pm$ ultramafic rocks bounding intensely imbricated horses in a duplex structure. If this scale of imbrication is representative of the entire outcrop width of mesoscale mélange in the McHugh Complex, then a transect from Tutka Bay to the Gulf of Alaska (40 km) would cross hundreds of imbrications of oceanic plate stratigraphy. As illustrated in Fig. 4, deep levels of these imbricate stacks may contain deep levels of the oceanic-plate stratigraphy, explaining the distribution of ultramafic complexes and their association with gabbro in locations including Halibut Cove (Fig. 2).

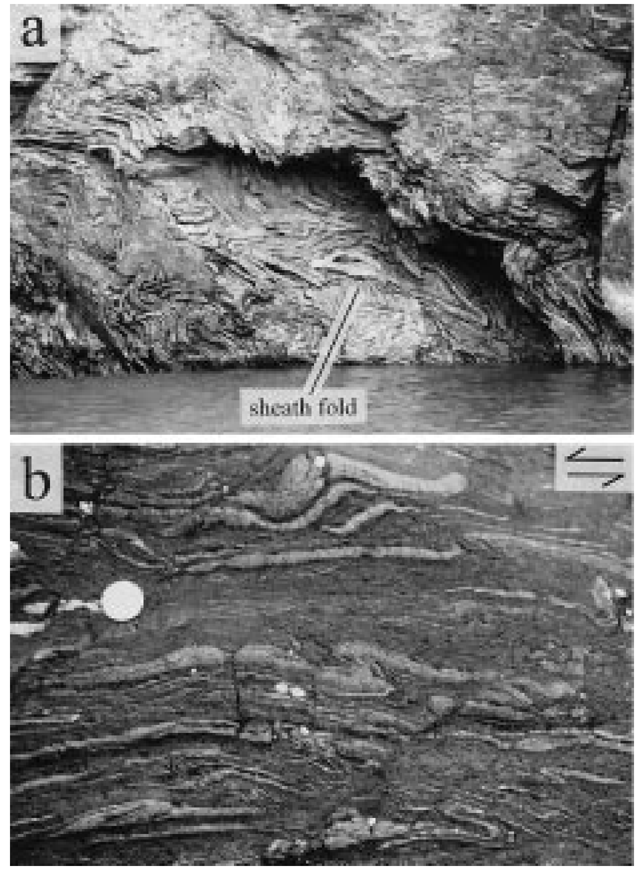

Fig. 5. Folds of layering in mélange units. (a) Sheath folded chert from Kachemak Bay (fold is approximately 3 m across), (b) folds in graywacke–argillite mélange.

4.1.2. Folds of layering in mélange

Folds are surprisingly rare in most locations and rock types in mélange of the McHugh Complex. A locally spectacular exception is provided by ribbon chert and argillite units within the mélange, which nearly everywhere exhibit complex disharmonic and more rarely sheath folding (Fig. 5a). This folding occurred after the formation of layer-perpendicular silica veins which commonly cut individual chert layers. In rare cases, graywacke–argillite (Fig. 5b) and greenstone–chert–argillite mélange units show trench-vergent folds that fold the fragment foliation and the scaly cleavage. These asymmetric folds are generally confined to layers that show high shear strains, and their vergence can be used to deduce the overall sense of shear across these high strain zones (e.g. Cowan and Brandon, 1994).

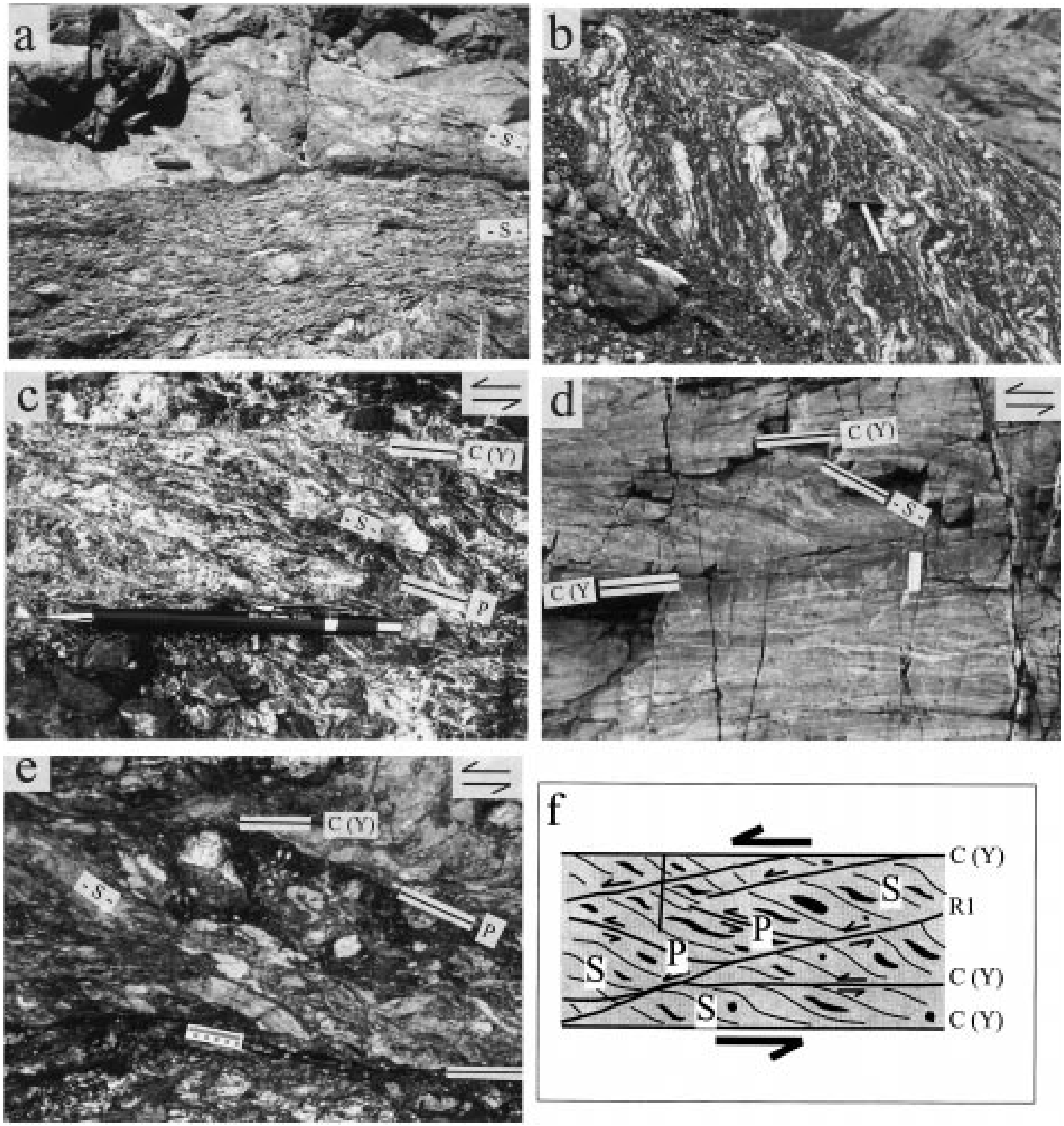

Fig. 6. Representative foliation styles in the McHugh Complex: (a) phacoidally cleaved mudstone mélange with small blocks or clasts of graywacke. Upper unit is graywacke cut by numerous small cataclastic shear zones, producing web structure. Note that fabrics are parallel to lithological layering in the argillaceous unit (bottom), and oblique to layering in the more massive graywacke unit (top); (b) chert–argillite mélange showing discontinuous nature of layering, produced by dense anastomosing shear zones. Wavy aspect is produced by thin chert and argillite layers wrapping around harder blocks, and a short-wavelength open folding; (c) *C–S* mesoscale mélange, showing through-going shear (*C*) surfaces, and fragment elongation (*S*) fabric; (d) *C–S* structure in graywacke–argillite mélange, (e) *C–S* structure in greenstone–argillite mélange; (f) kinematic framework of *C* (*Y*), *S*, *P*, and R_1 fractures in mélange.

4.2. Extensional structures

4.2.1. Phacoidal cleavage, C–S foliations, and R_1 (Riedel) fractures

A scaly or phacoidal foliation is present in most of the argillaceous, chert, and mudstone-matrix mélange belts (Fig. 6), and this is nearly everywhere close to parallel to the original lithological layering, resulting in layer-parallel extension both parallel to strike and down-dip. We assign S_1 nomenclature to this layering, but recognize that it is truly a composite $S_0 + S_1$ planar fabric. In some instances S_0 (original layering) and S_1

are clearly distinguishable. In cases where the scaly or phacoidal cleavage transects original lithologic layering, it extends these layers parallel to the cleavage. All gradations, from continuous S_0 layering cut by an anastomosing scaly fabric, to a scaly anastomosing fabric with inclusion trains of a different rock type, are present. The scaly cleavage is typically a composite fabric, with two or more orientations present, but since these tend to anastomose, they are not in most cases assigned a *C–S* type of terminology. A linear fabric (L_1) within S_1 is defined by the elongation of inclusions, and more rarely, by a lineation on the scaly argillaceous units. Clast elongation lineations may be down-dip, oblique, or parallel to strike, suggesting that there has been extension in several directions parallel to layering associated with large-scale flattening perpendicular to layering. Some additional elongation of inclusions parallel to strike may be caused by the intersection of anastomosing shear surfaces, much as described by Fisher and Byrne (1987) and Byrne and Fisher (1990) for the Ghost Rocks Formation on Kodiak Island.

Some of the argillite-matrix mélange units exhibit two foliations geometrically analogous to *C–S* structures in quartzo-feldspathic mylonites (e.g. Lister and Snoke, 1984), and *Y–P* fractures in some brittle fault zone rocks (e.g. Rutter et al., 1986; Chester and Logan, 1987; Kusky et al., 1987). These 'meso-scale *C–S* mélanges' are characterized by elongate fragments of chert, basalt, graywacke, and limestone, associated with an anastomosing scaly fabric parallel to the fragment elongation, and cut obliquely by through-going shear surfaces (Figs. 6c–e). Fig. 6(f) illustrates the geometric relationships between the various planar elements in these *C–S* mesoscale mélanges. The *C* (*Y*) surfaces are typically characterized by disaggregated sandstone, basalt, or chert fragments surrounded by a scaly argillite matrix. The *S*-surfaces are defined principally by the shape-elongation of the fragments, and by a preferred orientation of phyllosilicates defining the anastomosing mélange foliation. Some discrete cataclastic shear zones (*P*-planes) form parallel to the *S*-surfaces, and have a synthetic sense of movement with respect to the *C* (*Y*) planes (Fig. 6f). The angle between the *S*- and *C*-surfaces is typically between 25 and 35° (Figs. 6c–e), and the fragments and phyllosilicates bend into parallelism with the *C*-surfaces near their juncture, forming sigmoidal fabrics. In many cases, faint slip striations are visible on these foliation surfaces oriented perpendicular to the intersection of the *C* and *S* surfaces.

The *C* and *S* surfaces are offset in many places by small extensional faults oriented about 30° CCW from, and have the same sense of offset as, the *C*-surfaces. These are R_1 (Riedel) shears (Fig. 6f). In some places the R_1 shears are present singly whereas in others they are present in groups, spaced every few to every few tens of centimeters. Similar structures have been noted in other fault zones (e.g. Rutter et al., 1986) and mélange (e.g. Kano et al., 1991).

Although the deformation mechanisms that produced the 'meso-scale *C–S* mélanges' are obviously different from the crystal–plastic mechanisms that produce *C–S* mylonites, the kinematic interpretation is the same (e.g. Cowan and Brandon, 1994). The *C*-surfaces are obvious shear surfaces that truncate lithological layering and are decorated by thin films of phyllosilicates, and the *S*-surfaces show fragment flattening and elongation in an orientation consistent with the sense of shear across the *C*-surfaces. In this regard, many outcrops of mélange of the McHugh Complex can be interpreted in terms of sense-of-shear in a manner analogous to interpreting thin-sections of quartzo-feldspathic mylonite (e.g. Cowan and Brandon, 1994). Most kinematic indicators from the McHugh Complex show oblique slip with the hanging wall moving up with respect to the footwall, consistent with an accretionary wedge setting.

4.2.2. Web structure

In sandstone- and greenstone-dominated belts, a complex cataclastic composite fabric (web structure) disrupts original layering. This appears in many cases to have accommodated a very large amount of layer-parallel extension, accounting for nearly complete obliteration of all primary textures, forming, in essence, a cataclasite. This 'web structure' (sensu Cowan, 1982) is best observed in massive graywacke and greenstone units, and may contribute to their characterization as 'massive' through total destruction of all primary (S_0) features. Individual surfaces are typically less than 1 mm in thickness, but characteristically form an anastomosing network of shear surfaces (see also Byrne, 1984; Cowan, 1985). Individual shear surfaces or groups typically segment the rock into blocks with similar shapes and sizes to inclusions in nearby mélange belts. In thin section, web structures are seen to be zones of grain size reduction through grain breakage (cataclasis), although enhanced concentrations of phyllosilicates along these zones suggests that diffusional mass transfer ('pressure solution') was also an important deformation mechanism involved in their genesis (e.g. Knipe, 1989).

4.2.3. Boudinage, asymmetric boudinage, and domino structures

Pinch-and-swell and boudinage are common mechanisms of layer-parallel extension in the McHugh Complex, and may be observed at the regional (e.g. the massive graywacke unit, Fig. 2), outcrop, and thin-section scales. Pinch-and-swell and boudinage is common in all the different types of mélange; in all cases

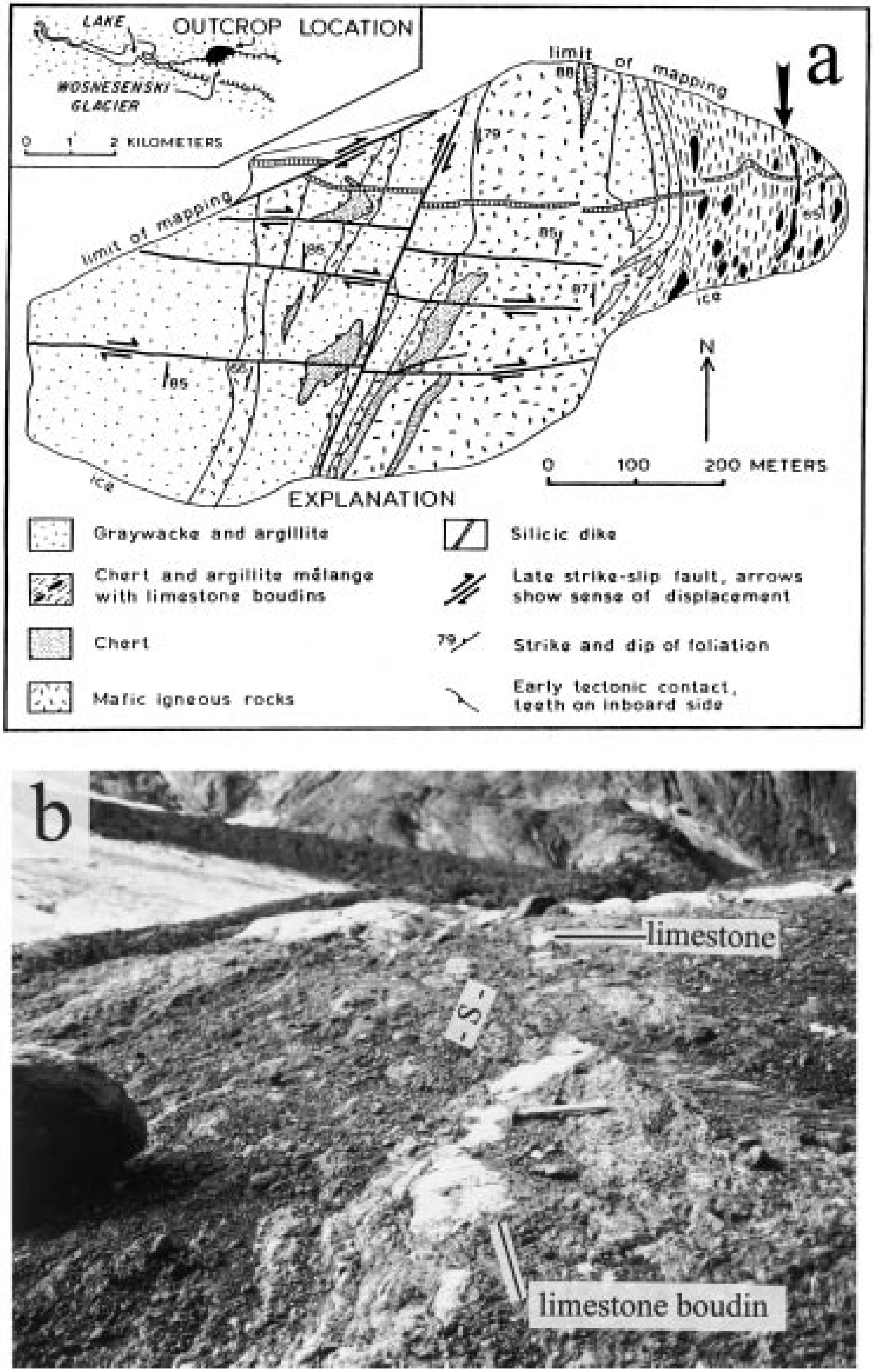

Fig. 7. (a) Geologic map of the toe of Wosnesinski glacier, showing long train of limestone blocks in argillite matrix. Arrow shows view direction of photo (b); (b) photograph of limestone blocks at Wosnesinski glacier.

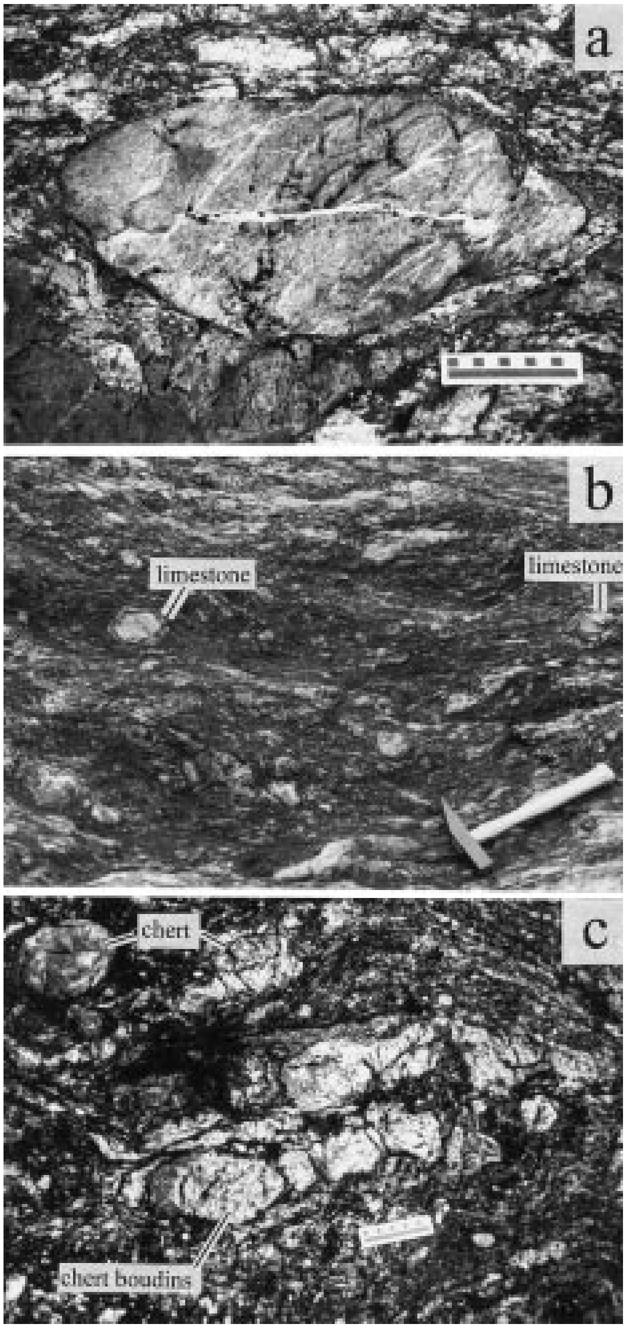

Fig. 8. Boudin types from the McHugh Complex. (a) Graywacke boudin showing two different orientations of extensional veins, (b) a train of rounded clasts of limestone rimmed by ankerite, (c) asymmetric boudins of chert in a chert–argillite mélange, showing thin boudin necks on the tip of the boudin, and wide boudin necks on the bottom of the boudin.

the stiff units are boudinaged in the weaker matrix. Sandstone beds form boudins in argillite-matrix mélange, chert blocks are formed through boudinage in chert–argillite mélange, and greenstone forms boudins (or schlieren, see below) in basalt–argillite mélange. In places where boudins are present along with *C–S* mesoscale mélange, the boudin necks are typically parallel to the *C–S* intersection lineation.

Limestone blocks form boudins or trains of boudins in an argillite matrix at several locations. One example is found at the toe of Wosnesinski Glacier (Figs. 7a and b), where a train of limestone boudins can be traced for approximately 200 m, suggesting that the boudins here once formed a continuous bed that has been extremely attenuated. A simple strain calculation (comparing the total length of all boudins with the total length of all boudins plus the interboudin distances) reveals that this bed has been extended by at least 600% parallel to strike within the foliation plane. No data are available for the amount of down-dip extension in this example. Other examples of isolated blocks of limestone in an argillite matrix within the McHugh Complex may represent cases of even greater extensional strains. Fig. 8(b) shows two rounded limestone 'clasts' rimmed by ankerite. In this location (Petrof Glacier), a train of these boudins was traced for several tens of meters, making it improbable that they formed by chaotic sedimentary disruption as an olistostrome.

Many boudins continued to extend after they became separated from their neighbors in the original layer. Fig. 8(a) shows a large graywacke boudin cut by two orientations of quartz veins, indicating extension oblique to and at a high angle to the boudin long axis. This geometric relationship suggests that the boudin rotated between the event that generated its shape and that which generated the quartz veins. The boudin is also cut by a brittle fault. A systematic orientation of extensional fractures perpendicular to early R_1 shears in boudins has been reported by several workers from accretionary complexes, including Needham (1987), Kimura and Mukai (1991) and Onishi and Kimura (1995). These workers suggest that the late-stage extensional fractures form through heterogeneous shear on the foliation planes.

Some layer-parallel extension in the McHugh Complex has created equant boudins with rounded necks, producing cross-sectional shapes that resemble sedimentary clasts. Fig. 8(c) illustrates a boudinaged chert layer in a silicified argillite-matrix mélange from the toe of Petrof Glacier (Fig. 2). This boudinage is unusual in that the upper and lower boudin necks have extended asymmetrically, perhaps related to different rheological contrasts between the chert and the upper and lower argillite layers (perhaps in turn related to different fluid pressures?). Also interesting in this example is the shape of the individual boudins. They have steep necks, forming well-rounded boudins, and if layer-parallel extension had proceeded further, would have produced chert blocks resembling sedimentary clasts. For both symmetric and asymmetric pinch-and-swell and boudinage structures, originally continu-

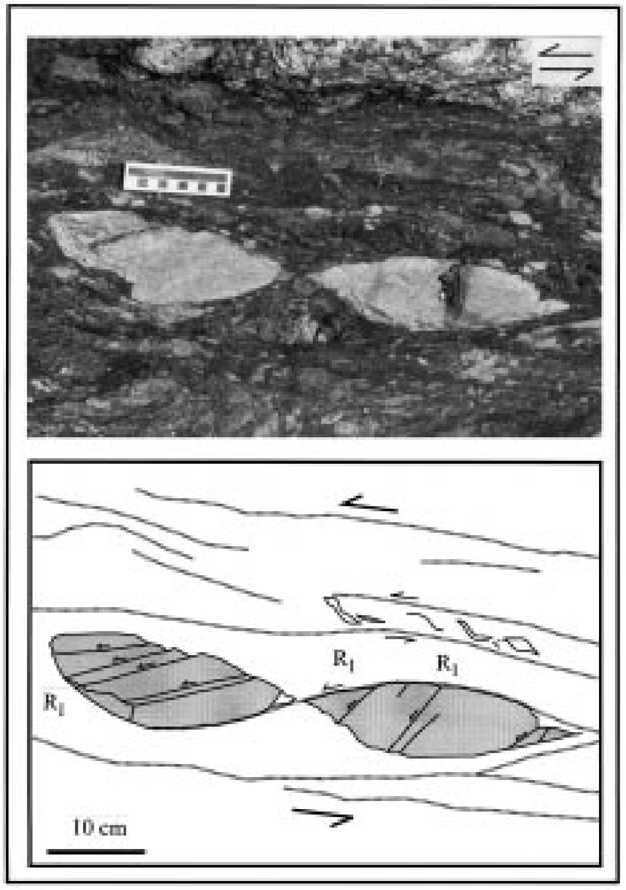

Fig. 9. Asymmetric boudinage and structural slicing along antithetic normal faults. Note the synthetic faults that have broken the boudins into domino-structures.

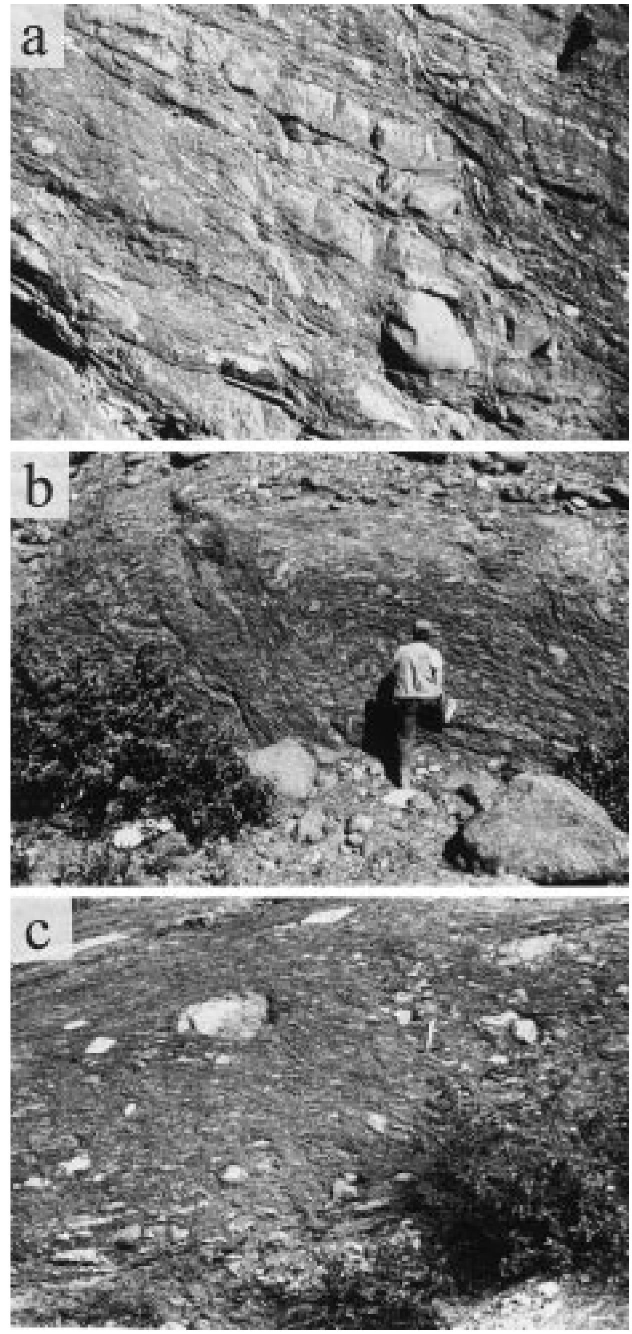

Fig. 10. Pebbly mudstone. (a) Graywacke argillite pebbly mudstone that has some tabular, flattened but not disrupted beds of graywacke, (b) outcrop of pebbly-mudstone cut by later shear zone, (c) pebbly mudstone showing clasts of graywacke and limestone.

ous layers can be traced into isolated inclusions in a scaly matrix. The progression from boudinaged chert layers to 'isolated competent blocks' in a chert–argillite mélange observed in outcrop suggests that the processes of boudinage and layer-parallel extension can produce isolated clasts of one rock type in a less-competent matrix.

Fig. 9 shows another mechanism of layer-parallel extension that produces blocks resembling boudins, but the mechanism of extension is not pinch and swell, but rather, slip along curved antithetic faults that merge with the matrix foliation. These correspond to Type II boudinage structures of Goldstein (1988), and the process involved is 'structural slicing' as described by Bosworth (1984). Note also that the boudins are cut by faults parallel to those that separate the two fragments. These are R_1 (Riedel) shear bands, and they have a sense of displacement synthetic to that of the matrix mélange (as determined from S–C structures, visible above boudins). In many places in the mélange, R_1 fractures like these break up competent layers into domino-like structures, with individual blocks back-rotated along the synthetic faults. The R_1 shears bend at their ends to merge with the matrix foliation. The sense-of-shear across individual layers in the mélange is easily determined using these 'domino' structures. The small steps visible on the fragments in Fig. 9 are a consequence of this type of rotation, along the faults visible in the photograph. Rotation along these R_1 faults can ultimately lead to separation of individual fragments (i.e. between the two fragments in

Fig. 9), and thus contribute to the fragmental nature of the mélange.

4.2.4. Broken formation and 'pebbly mudstone'

One of the more difficult rock types to interpret are the fragmental units consisting of clasts of one or more rock types within an argillaceous matrix, found within belts of mesoscale mélange. One sub-type, broken formation (sensu Hsü, 1974), consists of originally interbedded sandstones and shales which have experienced layer-parallel extension, forming discontinuous blocks of sandstone in an argillite matrix (Type I mélange of Cowan, 1985). Fig. 10 illustrates three stages in the evolution of broken formation from the McHugh Complex. The broken formation grades from nearly continuous sandstone–argillite beds (Fig. 10a) to a unit (Fig. 10b and c) which has been both extended along brittle faults and ductily thinned by pinch and swell processes. At these advanced stages of extensional disaggregation, the broken formation is an entirely disrupted rock type colloquially named 'pebbly mudstone' (after Hsü, 1974). The 'pebbly mudstone' is one of the most problematic of all rock types in the mélange. This term is not meant to imply a sedimentary origin, but merely that individual fragments of graywacke are engulfed within an argillaceous matrix, and that the spacing between similar fragments is large, such that there is no apparent way in which to match up or restore most individual trains of fragments.

In most cases it is impossible to unequivocally determine whether 'pebbly mudstones' were produced by sedimentary or tectonic processes, but several authors have suggested that other examples of 'pebbly mudstone' units with broad similarities to the McHugh 'pebbly mudstones' may be produced by either process (e.g. Hsü, 1974; Brandon, 1989; Steen and Andresen, 1997). Several observations suggest that most 'pebbly mudstones' of the McHugh Complex have been produced by tectonic and not sedimentary disruption. First, there is a continuum of fabric styles from continuous layers, through broken formation and 'isolated competent clasts' in a scaly matrix, to the 'pebbly mudstones'. Second, in rare cases (e.g. Fig. 10a), some thick strong layers within the 'pebbly mudstone' remain relatively tabular, suggesting that they have not been through a chaotic slumping or olistostromal process. Third, individual trains of lithologically distinct boudins can still be traced out within the 'pebbly mudstones' suggesting that they have not been chaotically slumped, but only severely extended.

Some of the pebbly mudstones are interpreted to have been plucked from the walls of, or injected along, fault zones. For instance, the thin pebbly mudstone mélange unit located about 100 m from the west end of Grewingk glacier island shown in Fig. 2 has clasts of limestone, mudstone, chert, basalt, and graywacke, and is sandwiched between belts of graywacke, chert and mudstone. It is unlikely that the basalt and other rock types found as clasts were originally interbedded in this thin interval, or in a potential olistostromal source area that shed these clasts only once and not in underlying or overlying units. It is much more likely

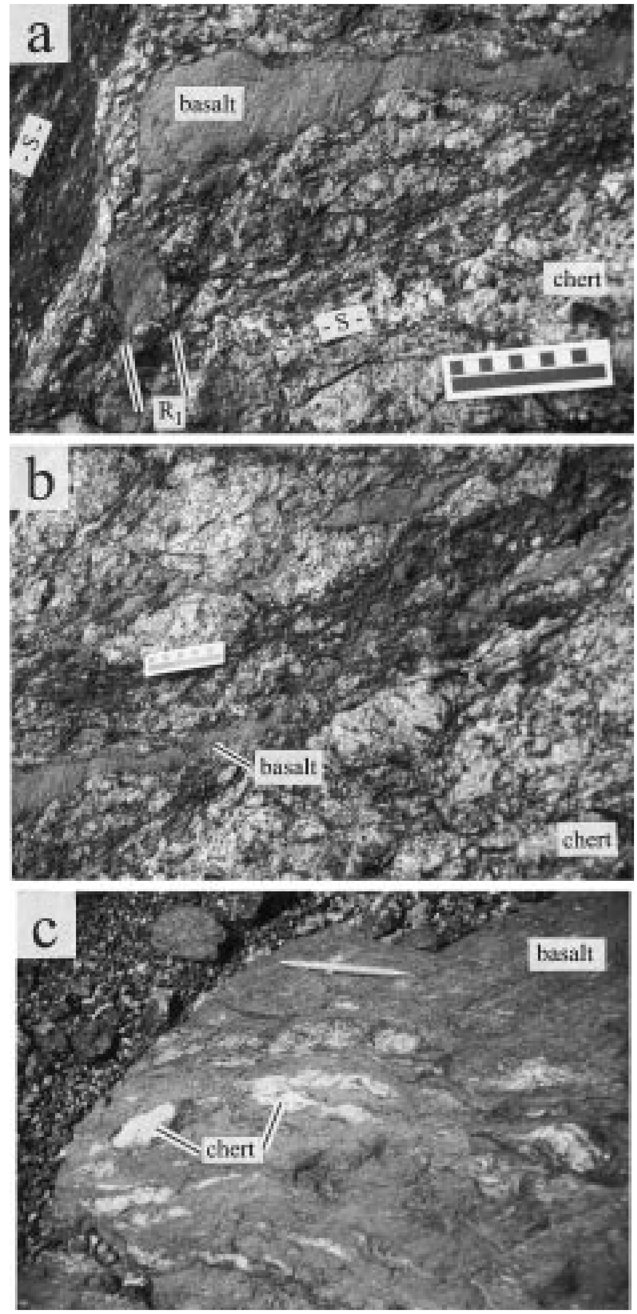

Fig. 11. Basaltic schlieren mixed with chert/argillite mélange (a and b). Basalt schlieren in (a) is truncated by a shear zone (with C parallel to S) at a high angle to schlieren elongation, and has associated R_1 shears that further disrupt the basaltic layer, and tend to isolate blocks of basalt within a chert–argillite matrix. (b) Strongly boudinaged end of the basalt schlieren. (c) Chert schlieren mixed with basaltic mélange.

that the pebbly mudstone is a tectonic mélange mobilized and injected along a fault at this horizon.

Another important observation is that pebbly mudstones consisting dominantly of graywacke blocks in an argillite matrix in some cases also have exotic clasts of chert, basalt, and limestone, but have no clasts of mélange. It is unlikely that the chert, basalt and limestone were originally interbedded with the graywacke–argillite, in an olistostromal source area that was shedding only competent clasts of graywacke, chert, basalt and limestone but not less-competent mélange. Most of the 'pebbly mudstones' were therefore most likely produced by tectonic processes, and might be more aptly termed 'pebbly tectonites'. Individual blocks were produced by tectonic processes, not by sedimentary abrasion and rounding. The term 'tectonic rounding' is suggested (after Hsü, 1974) for the production of such blocks or clasts in mélange.

4.2.5. 'Schlieren'

In numerous places throughout the McHugh Complex, thin layers or 'schlieren' (to borrow an igneous term) of one rock type occur within a different type of mélange. For example, Fig. 11 shows a thin cataclastically remobilized basalt layer within a chert–argillite mélange. It is not known whether this basalt was originally interbedded, intruded, or structurally mixed with the chert. In many cases, thin layers of cataclastically remobilized greenstone are so intimately mixed with argillite or chert, that isolated lozenges of each rock type may be found enclosing the other. The greenstone schlieren shown in Figs. 11(a) and (b) are 'frozen' in the process of being further extended and broken up by two separate processes. Fig. 11(a) shows Riedel shears cutting the greenstone layer, and merging with a larger shear zone in the mélange. These minor faults cut the greenstone layer into smaller pieces, and further, they take individual pieces of the greenstone out of the plane of the folia in which they were previously extended. Fig. 11(b) shows the tip of the same greenstone schlieren where it is more highly boudinaged and extended within the foliation by pinch and swell processes.

Similar cataclastically remobilized basalt is commonly designated as 'tuff' in the Chugach–Prince William Terrane (e.g. Byrne, 1984), but Decker (1980) has shown that these have a MORB chemistry, indistinguishable from adjacent massive and pillowed basalts, making it unlikely that these cataclastically deformed layers are truly tuffaceous. Many may represent dikes or sills that intruded the ocean floor sediments or accretionary wedge, consistent with intrusive relationships observed between 'tuff' and chert at Petrof and Battle glaciers. The association of 'remobilized cataclastic basalt' almost exclusively with the chert–argillite mélange suggests further that intrusion

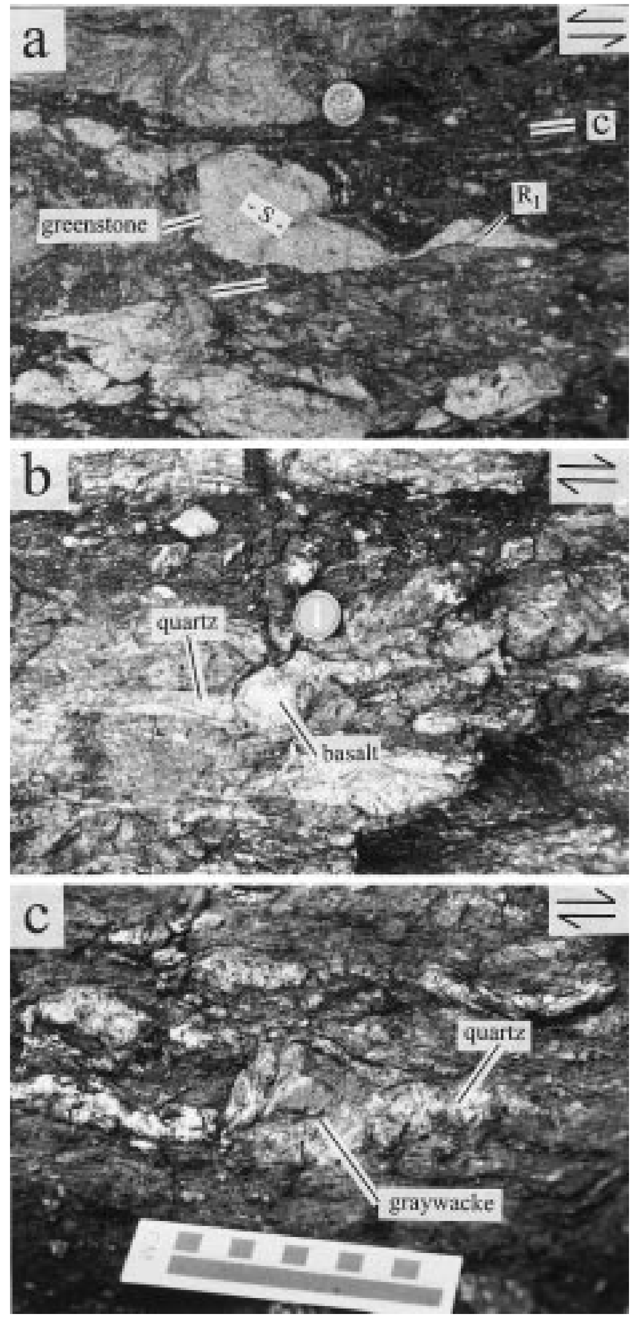

Fig. 12. Asymmetric structures around blocks indicating kinematics in mélange. (a) Block of cataclastized basalt in basalt–argillite mélange. The sense of offset on minor faults, the asymmetry of the tails, plus the orientation of R_1 fractures indicate sinistral shear. (b) Asymmetric tails of cataclastically remobilized basalt around a basalt block, indicating dextral shear. (c) Asymmetric tails of recrystallized quartz in the pressure shadow regions around a block of graywacke in graywacke–argillite mélange.

was likely to be related to off-axis sea floor volcanism. Other cataclastically remobilized basalt and mélange appear related to shear zones, where low-viscosity (fluid-rich?) mélange along shear zones locally injected rocks along the shear zone margins. One such example is visible in a mélange-rich shear zone that forms the boundary of the blueschist terrane at the head of Seldovia Bay (Fig. 2).

Fig. 11(c) shows another common type of schlieren: chert layers enclosed within cataclastically deformed greenstone. Whether these are chert 'xenoliths' caught within intrusive basalts, or represent interpillow chert horizons, is unknown. The greenstone is laced with a network of thin cataclastic shear zones (web structure), surrounding numerous chert/silicified argillite layers.

4.2.6. *Asymmetric pressure shadows around mélange blocks: meso-scale porphyroclast systems*

Numerous large competent blocks in the mélange have asymmetric block–matrix foliation patterns, pressure shadows, and recrystallized tails consistent with their interpretation as mesoscale porphyroclast systems. Fig. 12(a) shows an asymmetric greenstone fragment in a cataclastically deformed argillite–graywacke matrix at Petrof glacier. The structure is also cut by two through-going *C*-shear surfaces near the top and bottom of the greenstone lozenge (note: the similar looking greenstone layer apparently offset dextrally from the lozenge discussed, is not a piece of the same fragment, but is restorable to a different layer out of the field of the photo). The angular relationship between the direction in which the fragments are elongated and the through-going shear surfaces is interpreted as a *C*–*S* fabric formed during sinistral shear. The fragment has unambiguous asymmetric tails of cataclastically remobilized greenstone indicating sinistral shear. These are offset sinistrally by small faults, and the lower right tail has R_1 fractures that break the tail into a sinistral domino structure. Fig. 12(b) illustrates a basaltic fragment with asymmetric tails indicating dextral shear—the tails, and a rim around parts of the clast are made up of cataclastically remobilized basalt and quartz veins that accumulated in the pressure shadow regions around the porphyroclast.

Asymmetric pressure shadows around blocks of basalt, sandstone and chert are not uncommon in the McHugh Complex, and we interpret them in a manner analogous to pressure shadows around porphyroclasts in higher-grade metamorphic tectonites (e.g. Passchier and Trouw, 1996). Fig. 12(c) shows a graywacke clast with asymmetric pressure shadows composed mostly of recrystallized quartz, indicating dextral shear.

5. Late structures

Mélange of the McHugh Complex is cut by numerous late faults, dikes, and joints. The Chugach Bay fault and associated Iceworm mélange post-date mélange fabric development in the McHugh Complex (Kusky et al., 1997b), and these are folded about northwest-striking axes (Fig. 2). The early mélange fabric, Chugach Bay fault, and Iceworm mélange are all truncated by several distinct sets of later structures, including (1) variably striking extensional shear bands, (2) ENE-striking dextral faults, (3) NNE-striking dextral faults, and (4) W- to NW-striking sinistral faults. The ENE faults formed contemporaneously with intrusion of intermediate to felsic dikes, as shown by apophyses of dikes cutting faults that cut the main parts of the dikes, and also by dikes which are offset by faults but have chilled margins against the faults. The timing of intrusion and movement on the ENE faults is bracketed by the 54–56 Ma $^{40}Ar/^{39}Ar$ ages for these dikes (Bradley et al., 1999b). These late faults typically are present in domains where one set predominates over others (Bradley and Kusky, 1992), but together the late faults form an orthorhombic fault set (e.g. Reches, 1983; Krantz, 1988, 1989) that contributes significantly to the discontinuous nature of individual lithological belts in the McHugh Complex (Kusky et al., 1997a).

The contemporaneity of dike intrusion and late faulting in the near-trench environment of the Eocene implies that both may be consequences of subduction of the Kula–Farallon ridge (Marshak and Karig, 1977; Hill et al., 1981; Plafker et al., 1989, p. 4287; Bradley and Kusky, 1992; Bradley et al., 1993; Kusky et al., 1997a, b). Dike opening directions cross tectonic strike and cluster about 345°, which may reflect the orientation of the slab window, or may be an adjustment of the critical taper of the accretionary wedge during ridge subduction (Kusky et al., 1997a). Complications arise, however, because of uncertainties associated with coastwise strike slip of the entire accretionary prism (Moore et al., 1983; Plafker et al., 1989; Bol et al., 1992), and orocline formation (Carey, 1955; Plafker et al., 1989).

6. Relative roles of sedimentary and tectonic processes in the formation of mélange fabrics in the McHugh Complex

Because the tectonic setting of mélange of the McHugh Complex is known to be within an accretionary prism that has not overridden a continental margin, conditions of deformation are known better than would be possible in ancient accretionary prisms. The large-scale regional principal stress was probably subhorizontal to gently seaward-plunging during deformation (but see also Byrne and Fisher, 1990), and 'strata' were initially subhorizontal and are now steeply dipping. Structural fabrics within the McHugh Complex developed by some combination of sedimentary and tectonic processes related to offscraping and/or underplating in the accretionary prism, independent

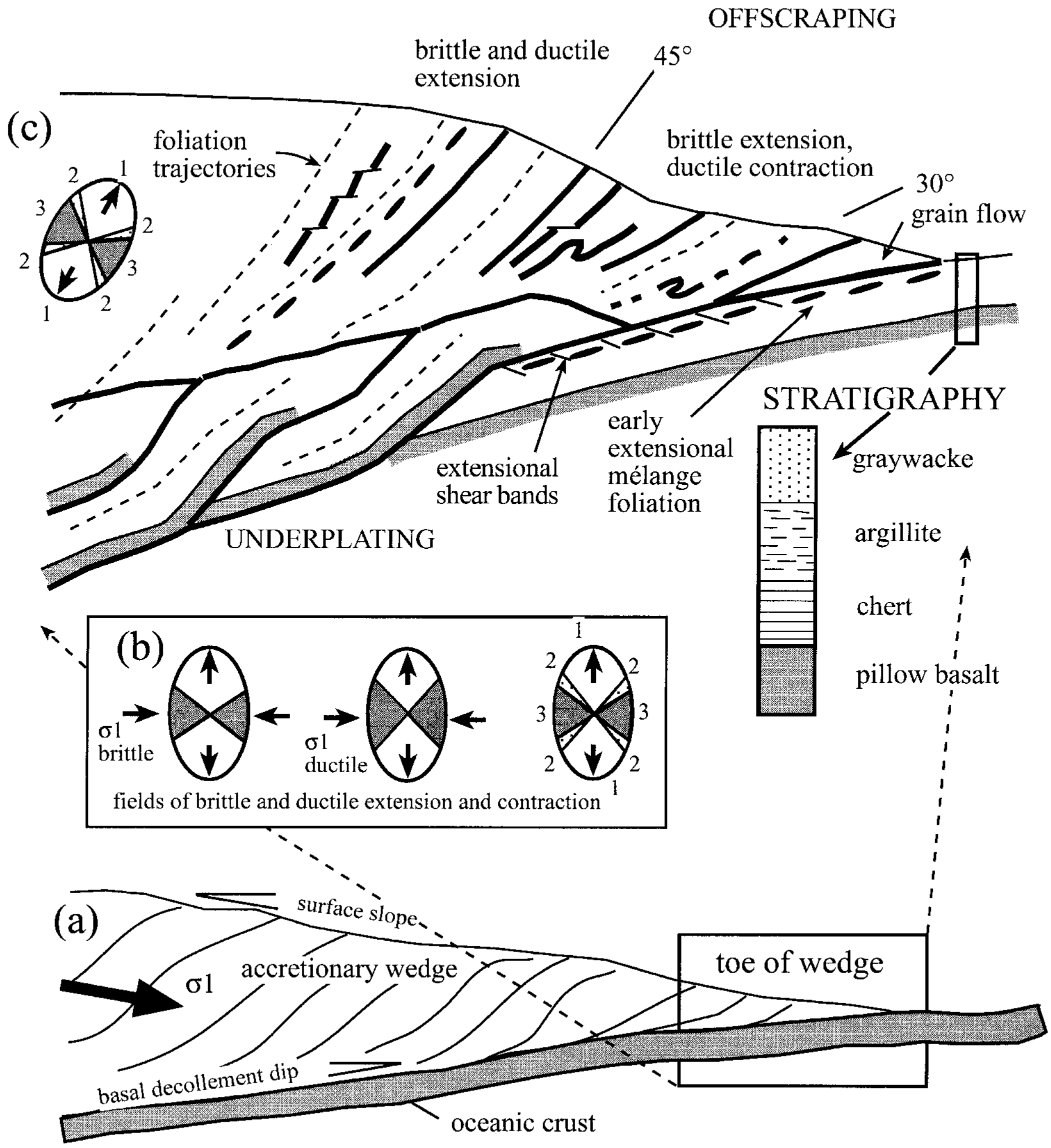

Fig. 13. (a) Schematic conditions of deformation in an accretionary wedge. σ_1 is slightly seaward-dipping to subhorizontal on a regional scale, and the critical taper (equal to the surface slope plus the basal décollement dip) is controlled by mechanical properties of the wedge. (b) Schematic diagram showing fields of brittle and ductile extensional and contractional (shaded) strains; brittle contractional strains occur in a field defining an acute angle about σ_1, whereas ductile contractional strains form a right angled field bisected by σ_1. Composite ellipse shows fields of brittle and ductile extension (1, not shaded), brittle extension and ductile contraction (2, dotted pattern), and brittle and ductile contraction (3, gray shade). In a lithologically complex setting such as an accretionary wedge, different rheological units will experience the brittle to ductile transition at different depths, so that there will be places in the wedge (c) where the different rheological units in the rock sequence are experiencing both brittle and ductile extension (layers $>45°$ to σ_1), brittle extension and ductile contraction (layers 30–45° to σ_1), and dominantly brittle and ductile contraction (layers $<30°$ to σ_1). Early extensional mélange formation (c) at a low angle to σ_1 is related to sub-simple shear in a zone of volume loss associated with early voluminous dewatering.

of any collisions with a continental margin. Since an oceanic plate stratigraphy can be reconstructed by matching original depositional and igneous contacts in the McHugh Complex, it is unlikely that mélange of the McHugh Complex was generated by downslope slumping or other mass wasting processes. Rather, it is fairly certain that the McHugh mélanges were generated by tectonic disruption at the toe of an accretionary wedge.

Most contacts between map units in the McHugh Complex are thin early faults and shear zones, characterized by uneven scaly surfaces formed by cataclastic processes. Many faulted contacts are only millimeters thick, and would be difficult to recognize after regional metamorphism characteristic of collisional mountain belts. These early thrust faults are nearly bedding-parallel, and are responsible for imbricating an oceanic plate stratigraphy grading downwards from graywacke and argillite, through chert, basalt, gabbro, and ultramafic rocks (Bradley and Kusky, 1992; Bradley et al., 1999a). Large amounts of layer-parallel extension in the lozenges between the early thrusts seem mainly responsible for the generation of mélange-type fabrics. Individual beds and layers become progressively pulled apart at higher strains, and ultimately form mélange characterized by blocks of a competent rock type (e.g. graywacke, limestone) in a less-competent matrix (e.g. shale, argillite). All stages of disaggregation can be traced, from continuous layering to 'isolated competent blocks' in a phacoidally cleaved matrix. In many cases the resulting tectonite strongly resembles a sedimentary conglomerate or pebbly mudstone (e.g. Brandon, 1989; Steen and Andresen, 1997), but that is purely tectonic in origin. The processes involved in producing these blocks or 'porphyroclasts' may be referred to collectively as 'tectonic rounding' (Hsü, 1974).

Hsü (1974) outlined some basic criteria by which tectonic mélanges can be distinguished from olistostromes, which are applicable to understanding the origin of the McHugh Complex. Among his criteria, Hsü noted that mélanges have tectonic contacts with adjacent units, whereas olistostromes have depositional contacts. Most contacts within the McHugh are tectonic; however, even within mélanges as complex as the McHugh, it is possible to find original depositional contacts within large composite blocks, and to reconstruct some original stratigraphic relationships (Bradley and Kusky, 1992; Bradley et al., 1999a). Mélanges have a phacoidally cleaved matrix, and contacts of blocks and matrix are tectonic, whereas in olistostromes, the matrix need not be pervasively sheared, and blocks may have depositional contacts with the matrix. Hsü noted that mélanges typically contain exotic blocks derived from the underlying tectonic element, whereas olistostromes do not, because they are deposited over the underlying unit.

Steen and Andresen (1997) described the characteristics and kinematics of structures associated with the emplacement of olistoliths, and found that emplacement-related structures typically include large listric normal faults. Associated structures include numerous minor extensional faults, contractional faults, asymmetric folds, and stratal disruption along the base and front of large olistoliths. Olistostromes may also be cut by later faults, yielding relationships more typical of mélanges.

Block–matrix age relationships may help distinguish mélanges from olistostromes. If a disrupted rock body has blocks younger than the matrix, it is necessarily a mélange and not an olistostrome (Hsü, 1974). Of particular interest, Hsü also suggested that fragment shape may be used to differentiate between mélanges and olistostromes. He noted that fragments (autoclasts) in mélange are bounded by shear surfaces, and typically have delicate intensely deformed tails trailing off into the matrix. Hsü suggested that the presence of very rounded clasts favors a deformed olistostrome origin for the fragmented rock body, but also noted that 'tectonic rounding' of clasts may occur if the clasts rotate during deformation and mélange formation.

The importance of 'tectonic rounding' in the generation of 'isolated competent clasts' and 'pebbly mudstones' is re-emphasized by the examples provided here for the McHugh Complex, and also in light of the body of evidence for highly noncoaxial deformation histories in accretionary prisms (Cloos, 1984; Platt, 1986). There are several different tectonic mechanisms very capable of producing rounded blocks in mélanges, particularly when the blocks rotate with respect to the stress field.

7. Deformation mechanisms and timing of fabric development in mélange

Structural analysis of mélange of the McHugh Complex has helped determine the timing and location in the accretionary wedge of the development of distinct fabric elements. One of the major remaining unknowns is when and where in the wedge specific structures formed with respect to changing material and mechanical properties of rocks during their deformation history (e.g. Davis, 1996). Broad constraints are placed on the depth of deformation by the ubiquitous prehnite-facies metamorphism observed in the McHugh Complex. Fig. 13 shows a schematic two-dimensional interpretation of a deforming accretionary wedge, incorporating aspects of models proposed by Silver et al. (1985), Fisher and Byrne (1987), Moore and Byrne (1987), Kimura and Mukai (1991), and Kusky et al. (1997b). This model is able to explain the sequence of structural development and range of structural styles observed in the McHugh Complex. Structures produced by early grain-flow deformation mechanisms grade into the development of web structure and extensional phacoidal cleavage with increasing depth along a downward-thickening fault zone marking the boundary between the thinly sedimented subducting plate and the accretionary prism. Web structure may represent a macroscopic three-dimensional network of faults analogous to the five independent slip systems needed to accommodate a general strain in crystal lattices (Lister et al., 1978; Lister and Hobbs, 1980).

Deformation in the thinly sedimented zone between the overriding and underriding plates may have been punctuated by periods of subduction of thicker sedimentary fans, perhaps explaining the thick accreted graywacke unit that stretches the length of the map area (Fig. 2). Material from this zone can be either offscraped and rotated into steeper attitudes as progressively younger material is offscraped, or it can be subducted, to be underplated, perhaps in a zone of duplexing as illustrated in Fig. 13. The duplexing imbricates an oceanic plate stratigraphy, explaining the repetition of graywacke–argillite, chert–argillite, chert–basalt, and ultramafic belts (Byrne and Fisher, 1987; Bradley and Kusky, 1992). In this model, the Kachemak Terrane of Jones et al. (1987) represents a duplexed slice of oceanic basement that escaped subduction and became incorporated as a large structural slice within the McHugh Complex. It may also account for how Red Mountain and other ultramafic–gabbroic massifs were brought to high structural levels within the McHugh Complex. Similar duplexing of the upper part of an oceanic plate stratigraphy has been documented in other mélange-dominated accretionary complexes, including the Cretaceous Franciscan Complex of California (Kimura et al., 1996), the Tertiary Setogawa of Japan (Osozawa, 1988), the Cretaceous Shimanto belt of Japan (Kimura, 1997), the Miocene of the Boso Peninsula (Hirono and Ogawa, 1998) and elsewhere in Japan (e.g. Isozaki et al., 1990; Kimura, 1997).

Two alternative hypotheses can account for the generation of extensional phacoidal cleavages like that in the McHugh Complex (Fig. 13). In the first model (pure shear), cleavages are inferred to form perpendicular to or at a high angle to σ_1, and since σ_1 is subhorizontal in accretionary wedges, the anastomosing scaly cleavage may have formed after the bedding was rotated into a nearly vertical attitude. In the second model (simple shear), S_1 is interpreted to have formed in a wide, downward propagating shear zone at the base of the accretionary prism (e.g. Silver et al., 1985; Moore and Byrne, 1987). After the beds are rotated into a steep attitude, they continue to internally extend, and many of the extensional structures including boudinage and phacoidal cleavages may continue to form. The geometry illustrated here (Fig. 13) suggests there will be places in the accretionary prism where late extensional fabrics will develop parallel to and be indistinguishable from early extensional fabrics, but there will also be places in the duplex zones where significant angles between the early and later foliations are expected.

Fig. 13(b) showing the fields of brittle and ductile extension and contraction illustrates an interesting phenomenon observable in fabrics of the McHugh Complex. Brittle fractures form an acute angle bisected by σ_1, whereas ductile shear zones form a right angle bisected by σ_1 (Ramsay and Huber, 1987). The diversity of rock types in mélange of the McHugh Complex suggests that some units will be experiencing brittle deformation while others are undergoing ductile deformation, at roughly the same position within the wedge. Using this relationship, fields are defined for which layers of suitable orientation will experience both brittle and ductile contraction at appropriate P–T conditions (field 3, gray shade), brittle extension and ductile contraction (field 2, stippled), or brittle extension and ductile extension (field 1, unshaded). Applying this principle to a simplified cross-section of an accretionary wedge, in which σ_1 plunges gently seaward, Fig. 13(c) defines fields as above, where layers of suitable orientation experience various combinations of brittle and ductile extension and contraction. Where the beds are at a low angle to σ_1 at the toe of the accretionary wedge, they will experience both brittle and ductile contraction, through folding and faulting, although much of the deformation here may be obscured by the partly unlithified nature of sediments at the toe of the wedge, and the dominance of grain-flow types of deformation mechanisms. As beds get rotated to higher dips (30–45°) they will experience brittle extension and ductile contraction (at appropriate depths), and at higher dips ($>45°$) they will experience both brittle and ductile extension, forming boudinage, and extension along a complex array of antithetic faults (Fig. 13). In addition, the rocks undergo significant changes in rheology from more ductile at the toe of the wedge to more brittle away from the toe, and layers and/or blocks with different rheologies (e.g. basalt vs argillite) may experience different deformation conditions at the same time in the same place.

The combination of high shear strains localized in a thin zone (on a thinly sedimented subducting slab), together with the varied brittle and ductile layer-parallel contraction and extension experienced by intensely imbricated units, is capable of producing the complex outcrop patterns of mélange of the McHugh Complex. This model explains the apparent paradox of contraction at one scale of observation and extension at another scale. Intense imbrication or repetition of units associated with layer-parallel shortening is commonly observed at the outcrop to seismic-profile scales from modern accretionary wedges, whereas extensional structures are associated with layer-parallel extension at the scale of individual layers (e.g. von Huene, 1979; Brocher et al., 1989; Fisher et al., 1989; Moore et al., 1991). The imbrication may largely follow extension (e.g. Fisher and Byrne, 1987; Byrne and Fisher, 1990), though parts of the wedge may experience simultaneous contraction and extension, as discussed here.

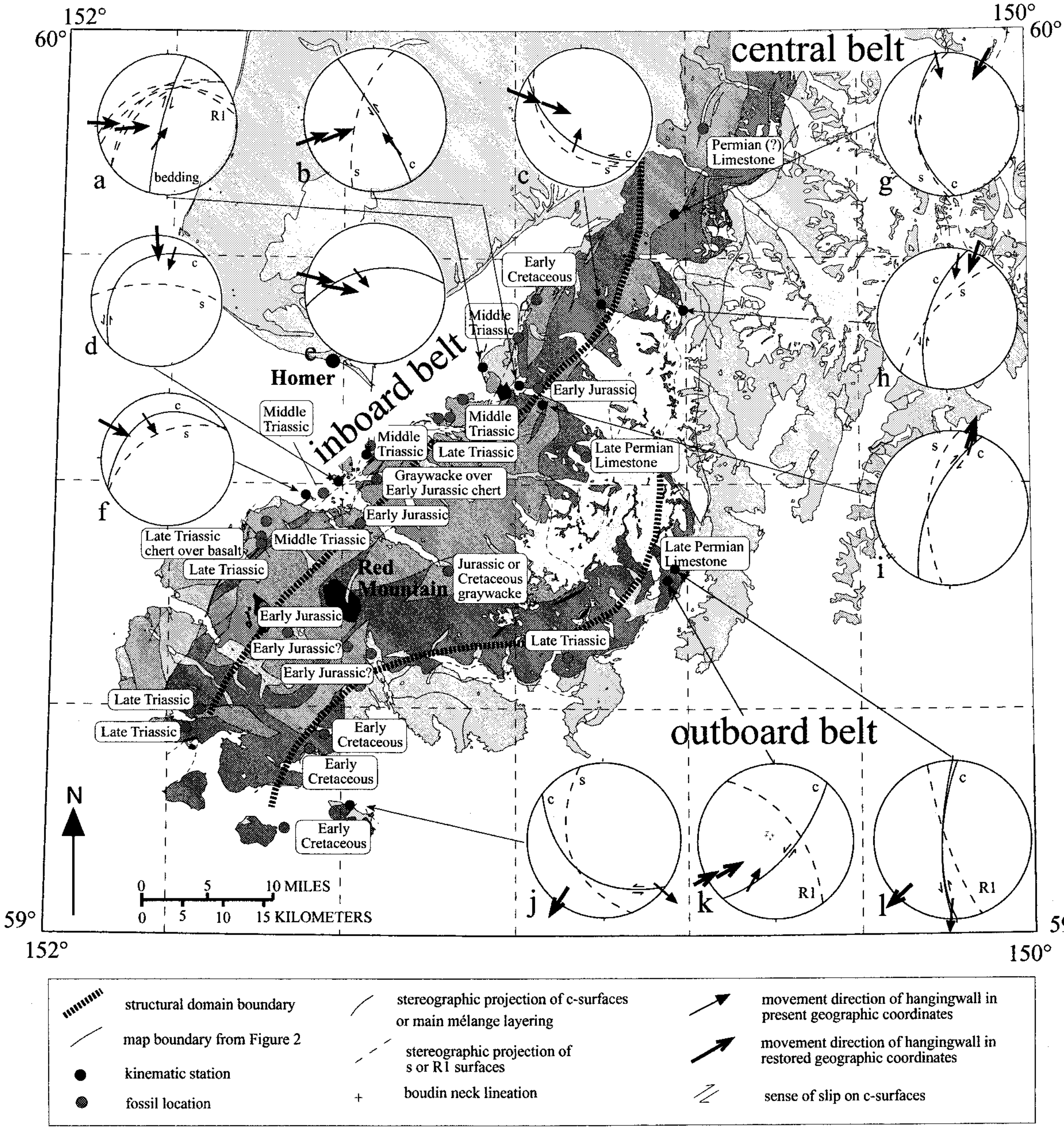

Fig. 14. Simplified map of the lower Kenai Peninsula showing locations of kinematic stations and the orientations of slip vectors in present day and restored coordinates (see Fig. 2 for explanation of units). Note that the McHugh Complex is divisible into three belts that show different kinematic patterns, including an inboard belt that shows E–W directed slip vectors, a central belt that shows NNE–SSW directed slip vectors, and an outboard belt that shows NE–SW directed slip vectors. Age calls are from radiolarians in chert except where noted. Note the overall seaward (SE) younging of ages of accreted material, from Late Triassic (240–210 Ma) in the inboard belt, through Early Jurassic (210–190 Ma) in the central belt, to Early Cretaceous (140–110 Ma) in the outboard belt.

8. Slip vector analysis and relationship to plate convergence directions

This section develops a method for interpreting the kinematic significance of the fabric asymmetry in mélange, following in part earlier work by Kano et al. (1991) and Cowan and Brandon (1994). Slip vectors can be derived from many of the structural elements present in mélange, and analyzed in a manner similar to kinematic data from higher-grade mylonitic rocks (e.g. Passchier and Trouw, 1996). However, rocks in mélange like the McHugh Complex commonly do not have well-developed slip lineations, so derivation of kinematic data is less direct. The following asymmetric fabric elements are used for kinematic analysis: (1) intersection of planar elements, such as C (Y), S, P, and R_1 surfaces, or between thrusts within duplex structures, with the slip vector lying at 90° to the intersection lineation, in the plane of slip (C); (2) slip or slickenline lineations on slip surfaces; and (3) fragment elongation lineations and boudin axes within S-surfaces of mesoscale mélange.

After measurement of these fabric elements in mélange, the most reliable data are plotted as a series of lower-hemisphere, equal angle projections and placed in the geographic framework of the regional map (Fig. 14). For each of the stations great circles for C (Y) surfaces are plotted as solid lines, S and R_1 surfaces as dashed lines, and the slip vector direction in present coordinates is plotted as a solid dot with an arrow through it pointing in the direction of slip of the hanging wall. Because rocks of the McHugh Complex have been rotated since formation of the mélange, and folded about vertical axes (e.g. Kusky et al., 1997b), several geometric corrections needed to be applied to the data to restore them to the best estimate of their original attitude. First, a rotation about a vertical axis was performed on the data to bring the local strike into parallelism with the regional 035° strike. Second, the data were rotated about a horizontal axis to account for tilting and/or folding of the layering in the mélange. Since the original attitude of the asymmetric fabrics is unknown, the rotated slip vectors are plotted for an attitude restored to a 30° NW dip for the main mélange foliation, and also in an attitude in which the slip vectors are restored to horizontal (Fig. 14). The assumptions inherent in such rotations are accounted for by plotting this range of possible initial orientations for the slip vector orientations of the hanging wall blocks in the mélange (note: where the difference in initial vector orientation is less than a few degrees, only one vector is plotted).

The area of interest is divided into three sub-parallel belts with different slip vector orientations (Fig. 14). The most inboard belt shows generally E–W-directed slip vectors, with one exception (d) coming from a chert unit that shows complex disharmonic folding on a regional scale (Kusky et al., 1997b; Bradley et al., 1999a). A central belt preserves NNE–SSW-directed slip vectors, and an outboard belt preserves NE–SW-directed slip vectors. Together, these slip vectors can be interpreted as a displacement field associated with the initial formation of the mélange.

The tectonic significance of the displacement field is less clear. In the simplest case, as the mélange grows progressively by successive offscraping events, each package will record the plate convergence direction at the time of accretion (e.g. Kano et al., 1991; Onishi and Kimura, 1995). By examining progressively younger (more seaward) mélange packages, a history of plate convergence directions may be reconstructed. In this sense, accretionary mélanges may record a kinematic history of convergence directions and plate interactions that occurred along a convergent margin during production of the mélange. Systematic analysis of mélange fabrics may therefore yield kinematic information complimentary to, and extending the temporal limit of sea floor magnetic anomaly data that are commonly used for plate reconstructions.

The ages of accretion within the kinematically defined belts in the McHugh Complex is presently only broadly constrained by the Toarcian (192 Ma) age of blueschist facies metamorphism in the Seldovia schist, by Pleinsbachian graywacke that depositionally overlies chert at Sadie Cove (north of Jackolof Bay) in the inboard belt (presumably recording the arrival of this package at the trench in the Lower Jurassic), and by cross-cutting Paleocene dikes (Bradley et al., 1993; Kusky et al., 1997a).

Sparse Middle Triassic to mid-Cretaceous ages of radiolarians in chert (C. Blome, cited in Bradley et al., 1999a) are depositional ages that must be older than accretion ages for each belt. The inboard belt contains dominantly Middle–Late Triassic radiolarian ages, the central belt contains mostly Early Jurassic radiolarians in accreted chert, and radiolarians from the outboard belt show dominantly Early Cretaceous ages (Fig. 14). Although there are exceptions to this generalization and data are sparse, there is a strong suggestion of seaward younging of ages of accreted cherts from 240–210 Ma in the inboard belt, through 210–190 Ma in the central belt, to 140–100 Ma in the outboard belt. Exceptions to this pattern may reflect out-of-sequence thrusting. The present constraints on the ages of accretion are therefore younger than 240–210 Ma (and locally circa 195 Ma) and older than 55 Ma in the inner belt, younger than 210–190 Ma and older than 55 Ma in the central belt, and younger than 140–100 Ma and older than 55 Ma in the outer belt. If the slip directions for each of these belts records plate kinematic information, the implication is that accretion was nearly perpendicular or slightly oblique to the orogen in the oldest interval recorded in the inboard belt, and then the orogen saw mainly oblique to orogen-parallel motions in younger events recorded in the two outer belts. Oblique accretion has also been postulated for parts of the outboard Valdez Group (and correlative Kelp Bay Group), based on subhorizontal mineral and stretching lineations (e.g. Haeussler et al., 1996; Davis et al., 1998).

One of the difficulties in interpreting the significance of slip vector orientations and regional displacement fields such as that derived above is that strain along convergent margins is often partitioned into belts of dominantly orogen-parallel and orogen-perpendicular displacements (e.g. Fitch, 1972; Dewey, 1980; McCaffrey, 1991, 1992, 1996; Avé Lallemant, 1996; Davis et al., 1998; Dolan and Mann, 1998). Strain partitioning should at least be suspected when belts of orogen-parallel displacements are documented, and strain partitioning is demonstrated when belts of orogen-parallel slip are shown to be contemporaneous with belts of orogen-perpendicular or -oblique slip. In order to differentiate which belts of different slip vector orientations may be related to changing plate convergence directions, and which may be related to strain partitioning, the precise timing of slip within each belt needs to be known. The age resolution for the McHugh Complex is currently not good enough to be able to differentiate between these two processes, as the age data only show a vague age progression of accreted rocks from Triassic to mid-Cretaceous. Fabrics related to orogen-parallel slip in zones of strain partitioning might be expected to be younger, and superimposed on earlier structures. Since all of the kinematic data reported here are from the earliest fabrics recorded in the McHugh Complex, it seems more likely that the kinematic pattern emerging from the McHugh Complex is related to oblique accretion than to strain partitioning. Furthermore, the slip vectors shown in Fig. 14 are oblique (not parallel or perpendicular) to the plate boundary, and are broadly compatible with changing plate kinematics during this interval as portrayed by Engebretson et al. (1985), Debiche et al. (1987), Atwater (1989), and Plafker and Berg (1994), with more oblique accretion preserved in the younger belts. Collection of additional detailed and systematic kinematic and age data from the McHugh Complex may shed further light on the accretionary history of the North American cordillera.

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